National Aeronautics and Space Administration

Detached Eddy Simulations of Hypersonic Transition

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Objective

- **Investigate the feasibility of using CFD in general, DES in particular, for prediction of *roughness-induced* boundary layer transition to turbulence and the resulting increase in heat transfer**

➢ ***Threat of overheating the delicate RCC wing leading edges was real.***

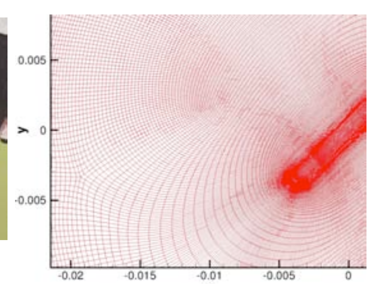
Hardware

- NASA Advanced Supercomputing Facility *enables* fine-grid unsteady turbulent flow simulations.

Software

- US3D code – Unstructured, parallel, finite-volume Navier-Stokes solver for thermo-chemical non-equilibrium hypersonic flows
- Detached Eddy Simulations (or WMLES) – Hybrid RANS/ LES approach
- Optional low-dissipation numerics


Wind tunnel model (1 mm high) compared with the Shuttle trip (6.35 mm high)



Unstructured hexahedral grid near the trip

Inviscid Flux Evaluation

$$\frac{\partial U}{\partial t} + \nabla \cdot (\vec{F} - \vec{F}_v) = W$$

Navier-Stokes equations for a mixture of species in conservation law form

Steger-Warming Flux Vector Splitting

$$F = F^+ + F^- = R^{-1}\Lambda^+ RU + R^{-1}\Lambda^- RU$$

$$F_{i+1/2} = (R^{-1}\Lambda^+ R)_i U_i + (R^{-1}\Lambda^- R)_{i+1} U_{i+1}$$

At a cell face

Modified Steger-Warming Flux Vector Splitting

$$F_{i+1/2} = (R^{-1}\Lambda^+ R)_{i+1/2} U_i + (R^{-1}\Lambda^- R)_{i+1/2} U_{i+1}$$

Lower dissipation!

$$\Lambda^{\pm} = (\Lambda \pm |\Lambda|)/2$$

Modified Steger-Warming Flux

$$F_{i+1/2} = \underbrace{\frac{1}{2}(R^{-1}\Lambda R)_{i+1/2}(U_{i+1} + U_i)}_{\text{convection}} + \underbrace{\frac{1}{2}(R^{-1}|\Lambda| R)_{i+1/2}(U_{i+1} - U_i)}_{\text{dissipation}}$$

Roe flux form

convection

dissipation

Baseline flux scheme

- *Original Steger-Warming Flux* — For shock waves
- *Roe Flux* — For smooth flows

Using a pressure dependent weight $w_{i+1/2} = 1 - \frac{1}{2}\left(\frac{1}{(5\delta p)^2 + 1}\right)$

High-order fluxes are obtained using the MUSCL approach with a weighted least-squares method to compute gradients.

Low Dissipation Flux

- Existing low-dissipation schemes to predict small turbulent eddies:
  - Skew-symmetric form to reduce the amplitude of the aliasing errors
  - Entropy function for secondary conservation law
- Present approach: Kinetic energy
  - Kinetic energy transport eq. derived from density and momentum eqs.
  - Combined with internal energy: $\rho E = \rho C_v T + \frac{\rho}{2} u^2$

Kinetic energy consistent flux

$$\sum_f (\rho k u' S)_f = \sum_f \frac{1}{2}(u_i u_{i+1} + v_i v_{i+1} + w_i w_{i+1})(\rho u' S)_f$$

Dissipative term from the modified Steger-Warming flux

$$d_{i+1/2} = \alpha \frac{1}{2}(R^{-1}|\Lambda|R)_{i+1/2}(U_{i+1} - U_i) \qquad \alpha = \frac{(\nabla \cdot \vec{u})^2}{(\nabla \cdot \vec{u})^2 + \|\vec{\omega}\|^2}$$

Implicit Time Integration

Baseline Scheme

Point Relaxation

$$(I + A^+_{i+1/2,j} - A^-_{i-1/2,j} + B^+_{i,j+1/2} - B^-_{i,j-1/2})\delta U_{i,j} = H_{i,j}$$
$$+A^+_{i-1/2,j}\delta U_{i-1,j} - A^-_{i+1/2,j}\delta U_{i+1,j} + B^+_{i,j-1/2}\delta U_{i,j-1} - B^-_{i,j+1/2}\delta U_{i,j+1}$$

Line Relaxation

For laminar sublayers only

(Modified Steger-Warming flux)

$$B^-_{i,j+1/2}\delta U_{i,j+1} + (I + A^+_{i+1/2,j} - A^-_{i-1/2,j} + B^+_{i,j+1/2} - B^-_{i,j-1/2})\delta U_{i,j} - B^+_{i,j-1/2}\delta U_{i,j-1} = H_{i,j}$$
$$-A^-_{i+1/2,j}\delta U_{i+1,j} + A^+_{i-1/2,j}\delta U_{i-1,j}$$

Data-Parallel Relaxation

$$(\tilde{A}^n - \tilde{C}^n)\,\delta U^k = H^n - \tilde{C}^n \delta U^{k-1}$$
$$\delta U^{n+1} = \delta U^{k\,\max}$$

- Original Gauss-Seidel not parallelizable
- *Replace the G-S sweeps with a series of point Jacobi-like iterations or a series of line relaxations.*
- Second order dual time stepping (KEC flux)

Detached Eddy Simulation

Spalart-Allmaras 1-eq. model with compressibility correction

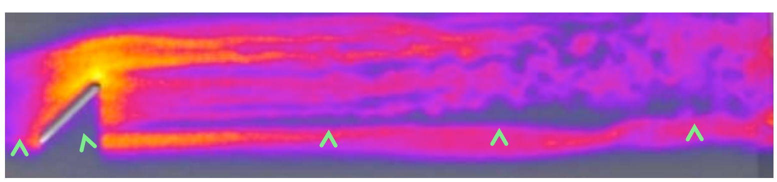
$$\frac{D\rho\tilde{\nu}}{Dt} = \underbrace{\nabla\cdot\left(\frac{1}{\sigma}\mu\nabla\tilde{\nu}\right)+\nabla\cdot\left(\frac{1}{\sigma}\sqrt{\rho}\tilde{\nu}\nabla\sqrt{\rho}\tilde{\nu}\right)+\frac{c_{b2}}{\sigma}\nabla\sqrt{\rho}\tilde{\nu}\cdot\nabla\sqrt{\rho}\tilde{\nu}}_{\text{diffusive transport}} + \underbrace{c_{b1}\tilde{S}\rho\tilde{\nu}}_{\text{production}} - \underbrace{c_{w1}f_w\rho\left(\frac{\tilde{\nu}}{d}\right)^2}_{\text{destruction}}$$

diffusive transport **production** **destruction**

- **RANS approach over-predicts the turbulent dissipation levels in separated flow regions.**
- **DES introduces a new length scale** $\tilde{d} = \min(d, C_{DES}\Delta)$
  - ***Model behaves like a subgrid scale model for LES away from the wall.***
  - **Wall-Modeled LES**

Test Case

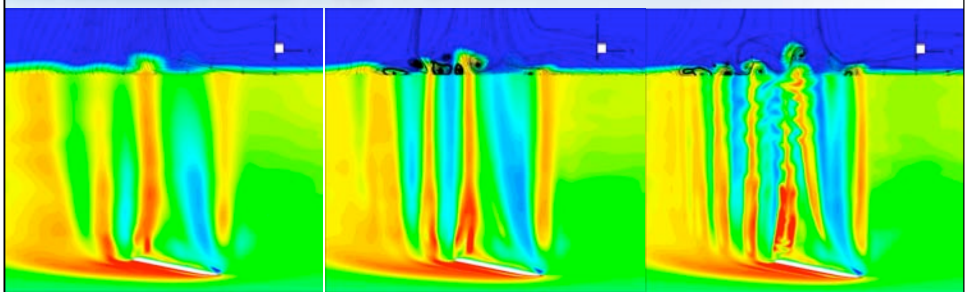
NASA LaRC Mach 10 wind tunnel experiment by Danehy et al.



Laminar Flow **BLT Trip** **Streak Instabilities** **Transition** **Turbulent Flow**

Flow conditions: M_{inf} = 9.93, Re_k ~ 6,000, T_{inf} = 51.3K, T_w = 308K

Grid Refinement Study



Coarse grid (15 M cells) solution using the modified S-W flux

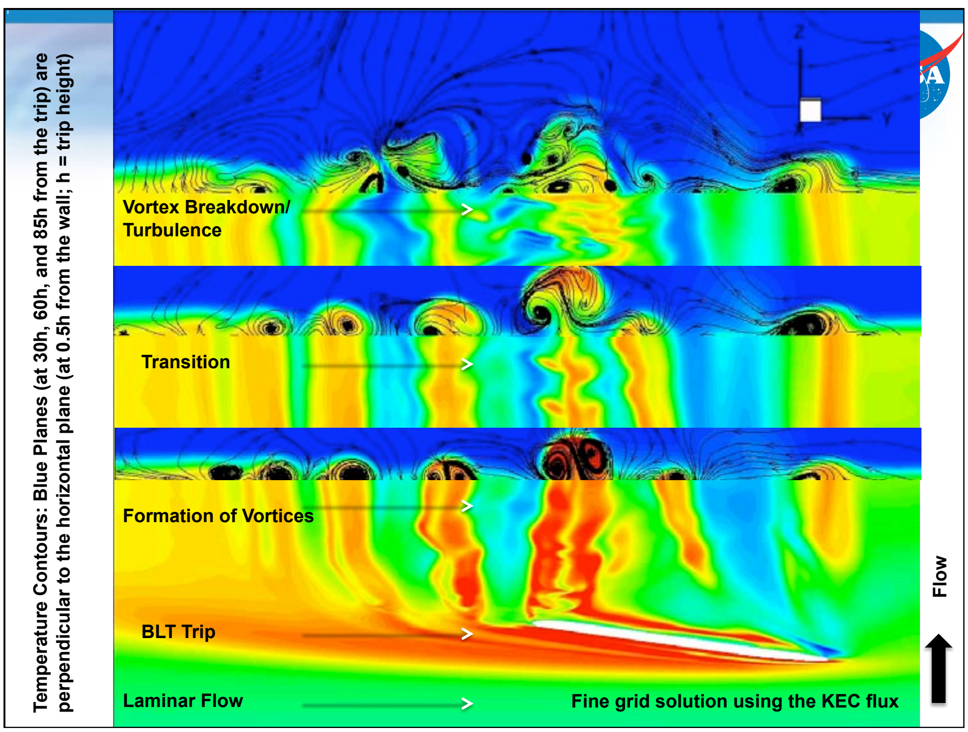
Medium grid (40 M cells) solution using the modified S-W flux

Fine grid (44 M cells) solution using the modified S-W flux (temperature contours)

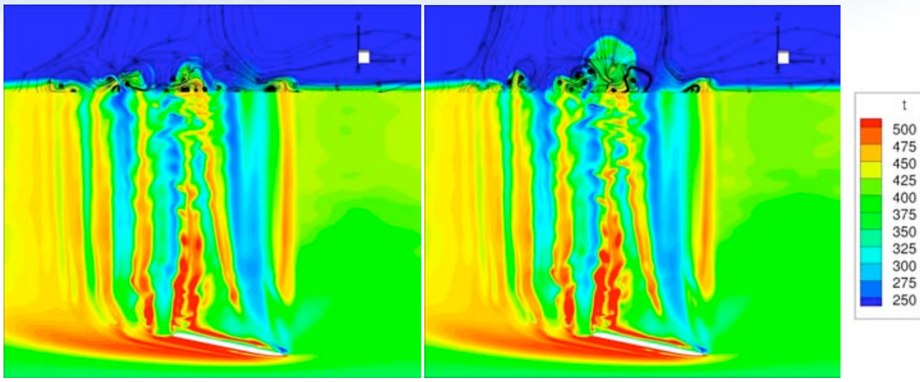
Grid requirements for DNS:

1B cells to resolve Kolmogorov dissipative scales

Grid points redistributed (grid density 2x)



KEC Flux Solutions

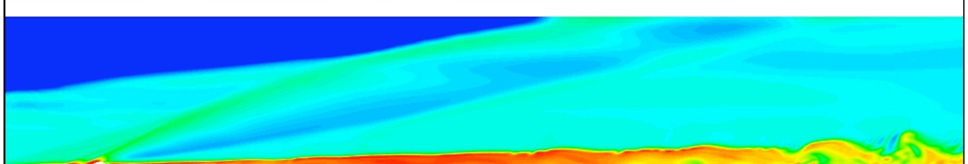


Fine grid solution using KEC flux with DES turbulence model

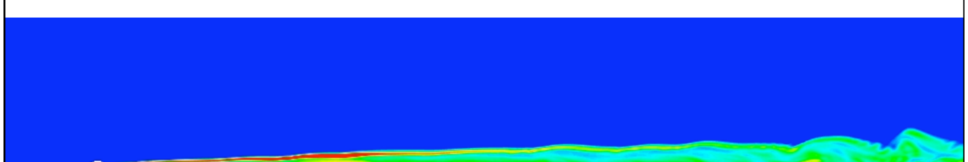
Fine grid solution using KEC flux without a turbulence model (ILES?)

- ***The accuracy of the turbulent flow solutions is driven primarily by the grid resolution.***

Side Views

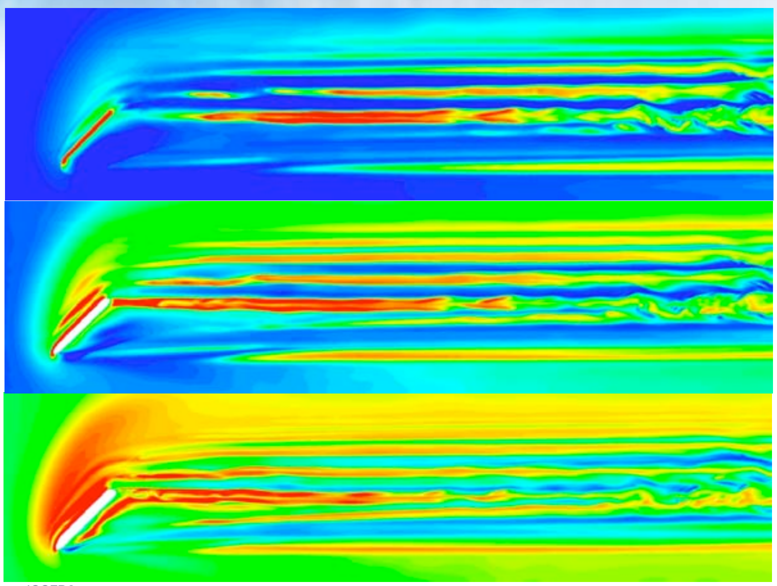


Temperature



Turbulent Viscosity

Top Views

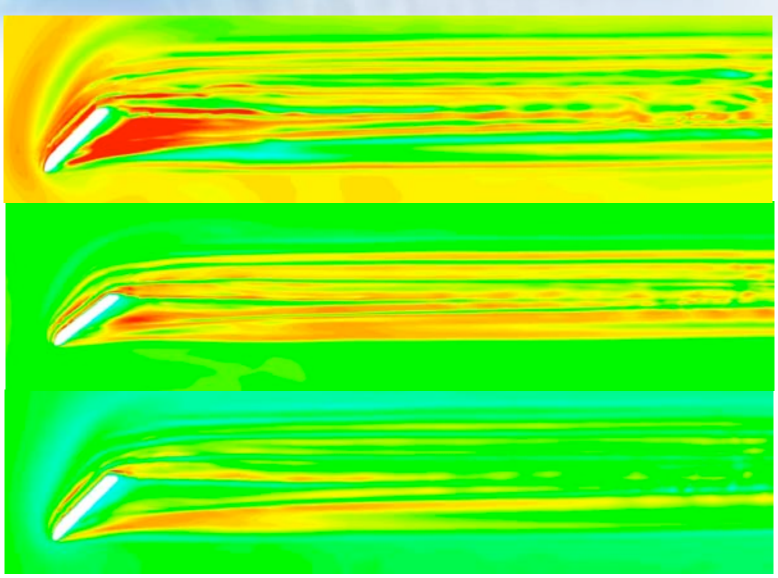


1.0 mm above the wall

0.75 mm above the wall

0.5 mm above the wall

Top Views (continued)

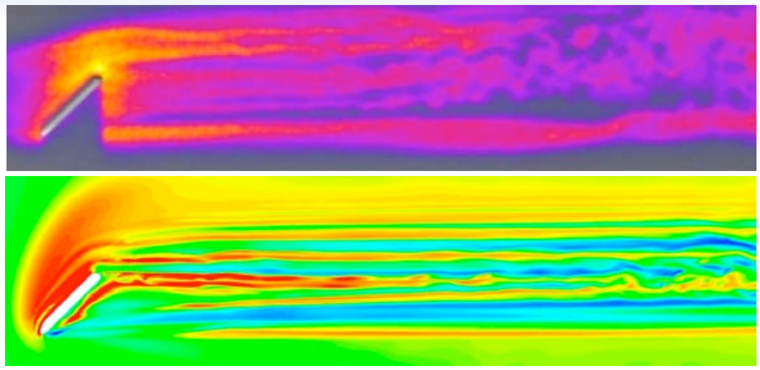


0.25 mm above the wall

0.1 mm above the wall

0.05 mm above the wall

Comparison



Experiment

Computation

0.5 mm above the wall

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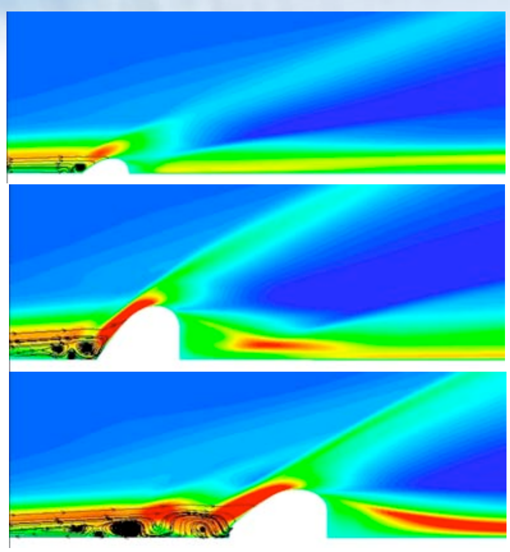
Formation of Upstream Vortices



4 mm from the center of the trip

(near the leading edge)

3 mm from the center of the trip

At the center of the trip

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Conclusions

- DES/ WMLES/ Hybrid RANS-LES can be a useful tool for predictions of hypersonic boundary layer transition to turbulence triggered by an isolated roughness element.
- It is necessary to use the low-dissipation kinetic energy consistent scheme on a sufficiently fine grid for an accurate simulation of transition.
- Accuracy of the turbulent flow solutions is driven primarily by the grid resolution.
- Interaction of vortices leads to vortex breakdown and hence turbulent flow.
- Computational results agree well qualitatively with the experimental observations.

Acknowledgments

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